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Annual Energy Consumption Analysis and Energy Optimization of a Solar-Assisted Heating Swimming Pool

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Abstract: This paper is concerned with the energy efficiency calculations and optimization for an indoor solar-assisted heating swimming pool in GuangZhou. The heating energy requirements for maintaining the pool constant temperature were investigated, which can be divided into three main parts: heat loss due to surface water evaporation, conduction and convective heat loss, and heat demand for heating fresh water. Then, an all-year solar radiation model for slope with varying orientation and incline angle is introduced, and relevant results are given based on typical year weather data in GuangZhou. Furthermore, annual energy consumption model and life cycle cost optimization model is established, and optimal results are analyzed based on an indoor solar-assisted heating swimming pool with 200m^2 surface area in GuangZhou.

Key words: Solar energy; Swimming pool; energy efficiency optimization

1. INTRODUCTION

During the last years of the twentieth century, extensive efforts to alleviate global warming of the earth caused by emission of carbon dioxide in atmosphere have been undertaken, these emissions are generated by intensive burning of fossil fuels [1]. The most important advantage of solar energy compared to traditional fossil fuels used for heating domestic water is that it needs few fossil fuels, therefore energy cost and environmental pollution decrease remarkably.

In recent years, solar-assisted heating system applied in swimming pool has attracted more and more attention in China. For constant temperature swimming pool in air conditioning room, the heating requirement depends mainly on fresh water temperature, indoor temperature, humidity and air speed, etc. Besides, daily acquirable solar energy flow is fluctuant according to actual radiation condition. For a given solar-assisted heating swimming pool, actual all-year energy consumption analysis is important in performing feasibility study based on annual pool heating load and local typical year radiation parameter. Furthermore, in order to obtain maximum economic payback, it is necessary to optimal selection the area of solar collectors, installation angle and orientation, and auxiliary heating equipment.

An indoor constant temperature pool in GuangZhou was selected as a case study, the main aim of this study is to appraise the annual energy savings characteristics under different area of solar collectors based on different incline angle, and life cycle cost model is also given.

2.HEATING LOAD OF INDOOR CONSTANT TEMPERATURE POOL

For a solar-assisted heating swimming pool, the heating demand is generally functions of hourly meteorological variables such as radiation, wind speed and temperature. Heat loss from an outdoor swimming pool occurs mainly by evaporation, convection and radiation. [2].

A indoor constant temperature swimming pool in a star hotel of GuangZhou (latitude 23.23°N, longitude 113.32°E) was selected for this study, the basic design parameters are shown as follows:

- Surface area of swimming pool is 200m^2, the average water depth is 1.5m;

- Indoor air temperature keeps constant, 28°C, relative humidity 60%;
- The design water temperature is 26°C; indoor air average velocity at water surface is 0.2 m/s.
- Daily opening time of pool is 12h.

For indoor swimming pool, the radiation heat loss and solar heat gain can be neglected, and heat loss of swimming pool can be divided into three main parts: heat loss resulting from surface water evaporation, conduction and convective heat loss, and heat demand for heating circulation water.

2.1 Evaporation Heat Loss

Evaporation is a major component of heat loss from swimming pool, and wind speed has a very close relationship with the rate of evaporation [3]. The rate of evaporation for the indoor pool can be calculated as equation (1) [4].

$$W = (0.0174V + 0.0229)(P_w - P_a) * 760 / B \qquad (1)$$

Where W is rate of evaporation from the pool (kg/m^{2}h); V is the indoor air velocity at water surface (m/s), P_w is saturation vapor pressure at the surface water temperature (mmHg); P_a is indoor air vapor pressure (mmHg); B is local atmosphere pressure (754 mmHg).

The evaporation heat loss Q_e (kW) can be calculated as follows:

$$Q_e = W \times A \times r / 3600$$

Where, A is water surface area of pool (m^2); r is latent heat of evaporation at pool temperature (kJ/kg).

2.2 Conduction and Convection Geat Loss

The convective heat loss Q_{c1} (kW) can be estimated by the following formula:

$$Q_{c1} = A \times h_c \times (T_p - T_a) / 1000 \qquad (2)$$

Where, h_c is convective heat transfer coefficient (W/m^{2}K), which can be expressed as a linear function of wind speed; T_p is pool water temperature (°C); T_a is indoor air temperature (°C).

Q_{c1} is very small compared to Q_e because the temperature difference between pool water and indoor air is only 2°C. Conduction heat loss Q_{c2} resulting mainly from the heat exchange between pool water and the wall and bottom of pool. According to design experience, Conduction and convection heat loss Q_c $(Q_{c1+}\ Q_{c2})$ is estimated approximately 20% of evaporation heat loss Q_e.

2.3 Supplement Fresh Water Heating

Fresh water must be supplied to maintain the total water volume of pool, besides, fresh water supplement is also useful for health of human. The heating requirement Q_{wh} (kW) can be estimated by the following formula.

$$Q_{wh} = \frac{c_p q_b (t_p - t_s)}{3600T} \qquad (3)$$

Where, C_p is specific heat capacity of water (4.187kJ/kg.℃); q_b is daily fresh water supplement flow (kg/d), which is estimated as 8% of total water mass of pool; t_s is fresh water temperature; T is opening hours of pool.

2.4 Total heating Load of Indoor Pool

Now, the pool total heating load Q (kW) can be expressed by summing up the aforementioned losses, which can be estimated as:

$$Q = Q_e + Q_c + Q_{wh} \qquad (4)$$

In order to obtain monthly average heating load Q of indoor pool, the monthly average fresh water temperature must be given, which can be approximated by monthly average wet bulb temperature in typical year. Monthly average wet bulb temperature in GuangZhou is shown as Fig 1.

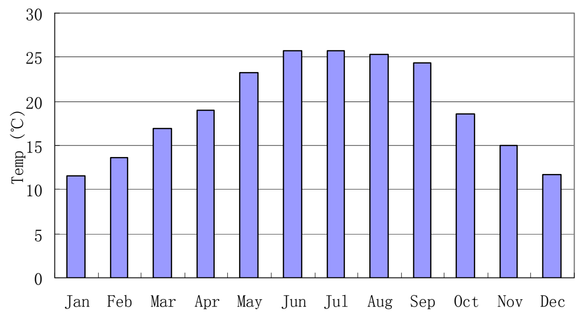


Fig 1 The monthly average wet bulb temperature in GuangZhou

According equation (1) ~(4), the monthly average heating load Q for maintaining constant temperature of indoor pool is calculated, shown as

Fig 2. As can be seen, the maximum heating load is estimated as 66.18kW that appears in January, and the minimum heating load is calculated as 33.08kW that appears in July.

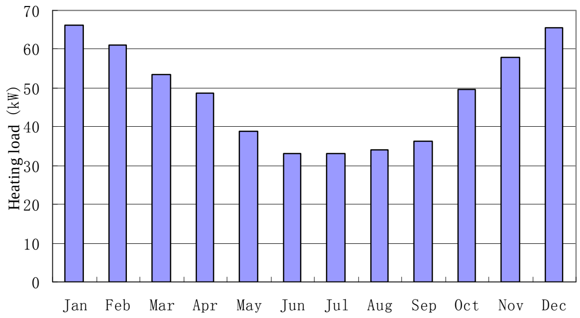


Fig 2 The monthly average heating load *Q* of indoor constant temperature pool

3. SOLAR RADIATION CALCULATION

In this paper, hourly solar radiation on horizontal plane in typical year in GuangZhou was obtained from literature [5]. According to statistics, the monthly average daily solar radiation on horizontal surface for the city of GuangZhou is shown as Fig 3.

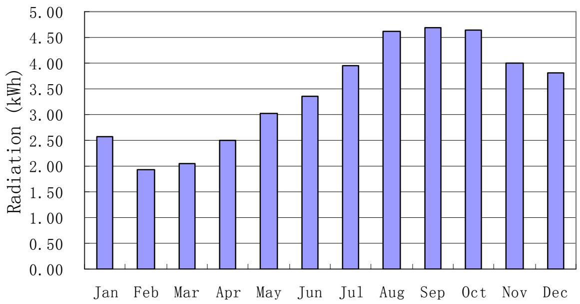


Fig 3 The monthly average daily solar radiation on horizontal surface in GuangZhou.

To improve the average monthly heat utilization characteristic, solar collectors were usually amounted at some incline angle and direction, and all-year total solar radiation summation and monthly solar radiation distribution attribute was changed accordingly. It is very necessary to obtain solar radiation data on slopes at any incline angle and any direction.

In this paper, diffusive and direct radiation separation method [6] is adopted for calculating hourly solar radiation on slopes at any incline angle and any direction when hourly solar radiation on horizontal plane in GuangZhou are given. According to a series of solar equations, the all-year total solar radiation summation on south-facing slope at 0~90° incline angle are compared as Fig 4, and monthly average daily solar radiation on south-facing slope at different incline angle (20°, 40°, and 60°) are shown as Fig 5.

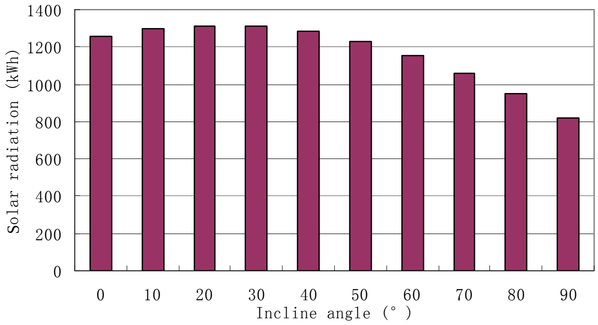


Fig 4 The all-year solar radiation summation on south-facing slope at 0~90° incline angle in GuangZhou.

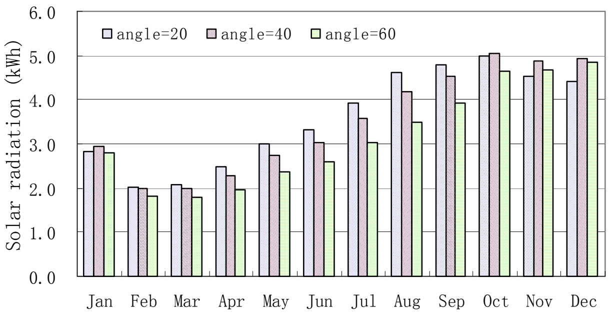


Fig 5 The monthly average daily solar radiation on south-facing slope at different incline angle (20°, 40°, and 60°) in GuangZhou.

According to related calculation and observation, the all-year solar radiation summation arrives maximum when slope faces south at incline angle with local latitude that can be proven by Fig 4. Owing to imbalance between solar energy resources and heating load of pool at different season, heating ability of solar collectors for given area always be surplus in summer and insufficient in winter. Furthermore, as can be seen from Fig 3 and Fig 5, average daily solar radiation in winter increases firstly, then decreases along with augment of incline angle, and average daily solar radiation in summer decreases all along with augment of incline angle, therefore, it is necessary to select reasonable incline angle in order to balance all-year solar energy distribution.

4. ANNUAL ENERGY CONSUMPTION CALCULATION AND COST OPTIMIZAITON

For solar-assisted heating swimming pool, supplement hot water boiler and heat storage tank is necessary owing to irregularity of solar energy resource. Hot water boiler must be put into operation when heat produced by solar collectors cannot satisfy the daily heating requirement of swimming pool.

During the whole year, primary energy consumption of hot water boiler can be estimated as follow formulas.

$$Fuel = \sum_{i=1}^{12} (N_i \times f_i(A_s, \beta) / \eta_{boiler}) \qquad (5)$$

$$f_i(A_s, \beta) = \begin{cases} Q_i t - Ra_i(\beta).A_s.\eta_{sc,i}, if\,(Q_i t \geq Ra_i(\beta).A_s.\eta_{sc,i}) \\ 0, if\,(Q_i t \leq Ra_i(\beta).A_s.\eta_{sc,i}) \end{cases} \qquad (6)$$

Where, *Fuel* is all-year primary energy consumption of hot water boiler (kWh); N_i is number of day in every month; subscript i is the index of each month (1,2,…12); t is opening hours per day of pool; A_s is area of solar collectors amounted (m^2); β is incline angle of south-facing solar collector; η_{boiler} is efficiency of hot water boiler; $f_i(A_s, \beta)$ is the monthly average daily heating load supplied by hot water boiler (kWh) under area A_s and incline angle β of solar collectors; $\eta_{sc,i}$ is monthly average thermal efficiency of solar collector; $Ra_i(\beta)$ is daily solar radiation under incline angle β (kWh/m^2).

In order to maintain the constant temperature of indoor swimming pool, all-year primary energy consumption can be calculated easily by equation (5) and (6).

To investigate the financial aspects of application solar collectors instead of conventional heating systems (only hot water boiler), the life cycle cost technique was applied, and annualized cost $\dot{c}$ is considered for evaluation and optimization in this paper. Owing to the hot water boiler and other auxiliary equipment is always necessary for solar-assisted heating pool or not, primary investment concerned with solar collectors is the only consideration. Annualized cost can be calculated by follow formulas.

$$\dot{C} = CRF(k,n).A_s.c_{sc} + Fuel.c_{pe} \qquad (7)$$

$$CRF(k,n) = \frac{k(1+k)^n}{(1+k)^n - 1} \qquad (8)$$

Where, *CRF* is capital recovery factor; k is interest rate; n is life of solar collectors; c_{sc} is unit price of solar collectors and auxiliary equipment (yuan/m^2); c_{pe} is unit fuel price of conventional hot water boiler (yuan/kWh).

For economic optimization, equation (7) can be objective function, and independent variable is incline angle β of south-facing solar collector and area A_s of solar collectors.

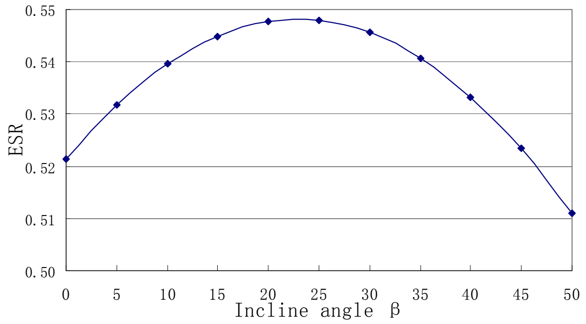
5. RESULTS AND DISCUSSION

Energy consumption evaluation and energy efficiency analysis is carried through for this case, based on assumptions as follows:

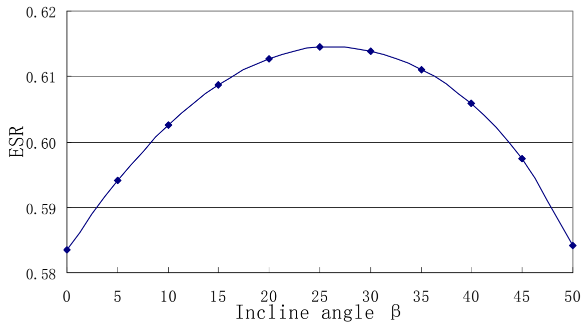
① A conventional gas boiler is selected as reference scheme, and η_{boiler} =0.88. All-year gas consumption is calculated as 239482.4kwh for reference scheme.

② Thermal efficiency $\eta_{sc,i}$ of solar collector is set as constant 0.5.

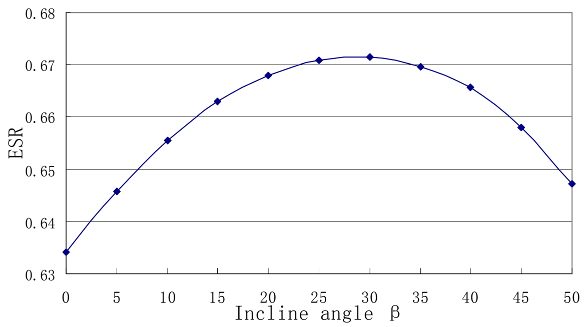
③ Relative energy save ratio *ESR* is selected as evaluation index, which is defined as *ESR=(239482.4-Fuel)/2394.82*.



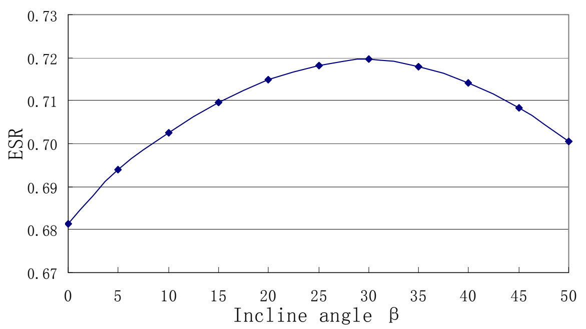
(a) A_s=175m^2



(b) A_s=200m^2



(c) A_s=225m^2



(d) A_s=250m^2

Fig 6. The effect of incline angle on *ESR* under different area A_s for south-facing solar collectors

Based on above analysis, it exits optimal incline angle of solar collectors for maximizing primary energy save ratio when collectors' area A_s is obtained.

For different installed area A_s of south-facing solar collectors, the effect of incline angle on *ESR* is shown in Figure 6.

As can be seen from Figure 6, optimal incline angle β increases with installed area A_s of south-facing solar collectors, which changes from 20° to 30°.

Furthermore, once unit price c_{sc} of solar collectors and unit fuel price c_{pe} of gas boiler is known, it is easy to select optimal A_s and β for minimizing annualized cost $\dot{c}$ by solving equation (7). The correlative results are not given in this paper.

6. CONCLUSION

Solar energy utilization has become a key technology in building hot water production, which can also applied in swimming pool heating. An indoor constant temperature swimming pool with 200m^2 located in GuangZhou was investigated, the monthly average heating load of pool was calculated based on indoor design parameters and meteorological data in typical year, and the maximum heating load of pool is estimated as 66.18kW that appears in January.

According to a series of solar equations, solar radiation on slopes at any incline angle and any direction can be obtained. Analysis shows it exits optimal incline angle of solar collectors to maximize energy save ratio when collectors' area A_s is given. Farther calculation indicates optimal incline angle changes from 20° to 30° according to different installed area of south-facing solar collectors in this case.

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